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The two main objectives of this work are to (1) develop an automated method for processing seismic and infrasound data from multiple seismo-acoustic arrays, and (2) to apply the method to a regional network of arrays for validation. The project involves development of automated techniques for detecting, associating, and locating infrasound signals at single and multiple arrays and then combining the processed results with similar automated procedures for seismic signals. This approach differs from most existing systems that typically depend on late association or data fusion after events are formed. Regional infrasound and seismo-acoustic events are automatically detected, associated and located using seismo-acoustic stations in Utah. We utilize the InfraMonitor toolbox, recently developed at Los Alamos National Laboratory (LANL), in collaboration with Southern Methodist University (SMU). The toolbox comprises an adaptive F-detector – which accounts for real ambient noise, and a robust signal association/event location algorithm. Seismic signals, obtained using a statistically based short-term average/long-term average (STA/LTA) detector, are associated with infrasound events obtained by InfraMonitor. A thorough ground-truth survey using satellite observations and independent data provides the basis for event identification. An analyst reviews automatic results in order to make a preliminary assessment of the number of false associations. We report on the numbers, distributions and sources of reviewed infrasound and seismo-acoustic events detected by Utah seismo-acoustic stations. Case studies of selected events provide examples of the infrasonic and seismo-acoustic records from regional events.

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**MULTI-ARRAY DETECTION, ASSOCIATION AND LOCATION OF INFRASOUND AND  
SEISMO-ACOUSTIC EVENTS IN UTAH**

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**ABSTRACT**

The two main objectives of this work are to (1) develop an automated method for processing seismic and infrasound data from multiple seismo-acoustic arrays, and (2) to apply the method to a regional network of arrays for validation. The project involves development of automated techniques for detecting, associating, and locating infrasound signals at single and multiple arrays and then combining the processed results with similar automated procedures for seismic signals. This approach differs from most existing systems that typically depend on late association or data fusion after events are formed. Regional infrasound and seismo-acoustic events are automatically detected, associated and located using seismo-acoustic stations in Utah. We utilize the InfraMonitor toolbox, recently developed at Los Alamos National Laboratory (LANL), in collaboration with Southern Methodist University (SMU). The toolbox comprises an adaptive F-detector – which accounts for real ambient noise, and a robust signal association/event location algorithm. Seismic signals, obtained using a statistically based short-term average/long-term average (STA/LTA) detector, are associated with infrasound events obtained by InfraMonitor. A thorough ground-truth survey using satellite observations and independent data provides the basis for event identification. An analyst reviews automatic results in order to make a preliminary assessment of the number of false associations. We report on the numbers, distributions and sources of reviewed infrasound and seismo-acoustic events detected by Utah seismo-acoustic stations. Case studies of selected events provide examples of the infrasonic and seismo-acoustic records from regional events.

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## **OBJECTIVES**

This project uses automatic detection, association, and location algorithms on regional seismo-acoustic array networks to build catalogs of seismo-acoustic events. To date, algorithms have been developed for robust detection, association, and location of infrasound and seismo-acoustic events. Each algorithm is designed for automatic near real-time application as part of a fully integrated seismo-acoustic monitoring system.

Validation of the method is done by applying it to one month's regional seismo-acoustic network data from Utah (Stump et al., 2007) and comparing automatic results with ground-truth information. We utilize direct ground-truth, Google Earth, and analyst review in order to assess the automatic results.

## **RESEARCH ACCOMPLISHED**

### **Detection, Association, and Location Algorithms**

Detections are performed with an F-detector (Blandford, 1974) modified to adapt to a variable scale parameter. This provides a detection null hypothesis that adapts to temporally variable ambient noise. First, F-statistics are computed for an adaptive time-window ( $w$ ), using the standard formula outlined in Blandford (1974). F-statistics are then scaled by a constant  $c$ , such that the peak of the distribution of F-statistics in the time window  $w$  aligns with the peak of the theoretical central F-distribution with  $2BT$ ,  $2BT(N-1)$  degrees of freedom. This follows from work by Shumway et al. (1999) who showed that, in the presence of correlated noise, the F-statistic is distributed as

$$cF_{2BT, 2BT(N-1)} \quad (1)$$

Infrasound signal association and event location are performed simultaneously using a forward approach. A grid-search procedure is implemented over a dense set of grid nodes that span the geographic region of interest. For each grid-node we search for sets of  $N$  arrivals at  $N$  arrays that can be associated based on backazimuth and delay-time constraints. Constraints, (backazimuth deviation,  $\Delta\phi$ , and group velocities,  $v_g$ ), must be set depending on the grid spacing used, an expectation of the maximum backazimuth deviation from winds ( $\Delta\phi$ ), and the range of infrasound group velocities ( $v_g$ ) suitable for a given region. Such constraints are chosen based on synthetic tests, as shown in the next section.

Seismic detection is performed on arrays using the same methodology described above. For single stations, we use a robust outlier detection on an STA/LTA power estimate. Briefly, STA/LTA is calculated on the time series power and the distribution of STA/LTA is transformed to a near-normal distribution using a Box-Cox power transformation. We then apply a standard robust outlier test to identify outliers that occur at  $>5$  median absolute deviations from the median. We perform seismo-acoustic association using infrasound events to search for associated seismic arrivals.

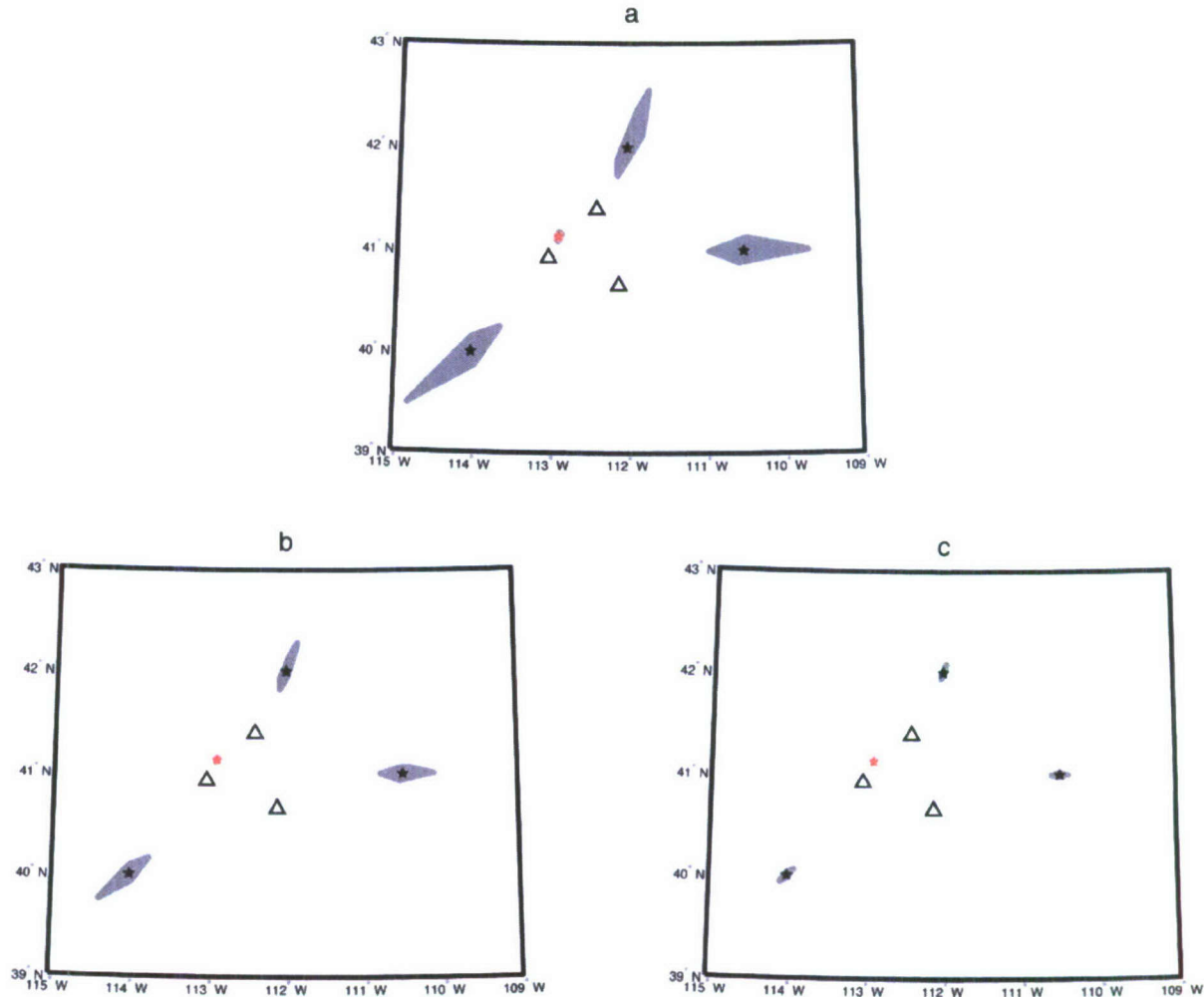
For further details on the methodology developed as part of this project, the reader is referred to Arrowsmith et al. (2008).

### **Synthetic Tests**

We performed synthetic tests to assess network location resolution and the effect of grid search parameters (i.e., allowed group velocities and backazimuth deviations). Each synthetic test considers several defined event locations and origin time. From the event definition, synthetic arrival times and backazimuths are calculated for each array using pre-defined group-velocities and assuming backazimuths to be great-circle paths. The set of synthetic arrival times and backazimuths thus constitutes the input to the previously described grid-search procedure.

Figure 1 shows the results for synthetic events based on the actual locations of arrays in the Utah seismo-acoustic network. These arrays each consist of four Chaparral gauges with the average spacing between gauges close to 100 m. Details of the installation can be found in Stump et al., 2007b. Four pre-defined event locations are defined, one at the Utah Test and Training Range (UTTR) a known ground truth location and three at arbitrary locations outside the network. The figure illustrates that as the grid-search parameters are increasingly constrained, the location uncertainties collapse to the known event locations (Figure 1). Reducing the uncertainty by constraining the grid search is done at the expense of missing some associations due to errors in event time or backazimuth estimates. In

an operational monitoring scheme where the automatic stage is used to select events for analyst review, it is necessary to select sufficiently relaxed parameters to ensure that no events are missed. For the Utah network, this results in corresponding location uncertainties shown in Figure 1a. These observations must be considered when interpreting the results described below. Uncertainty estimates are strongly dependent upon the array geometry and the location of the event of interest.



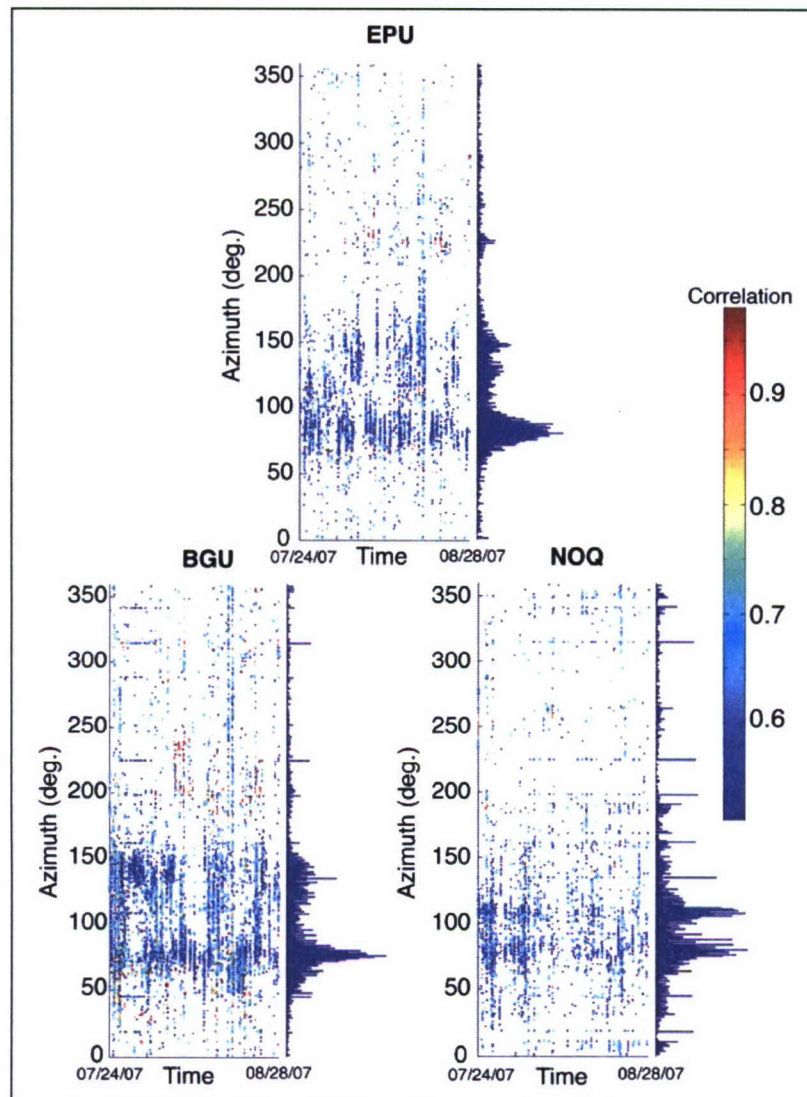
**Figure 1. Results of synthetic association/location tests for four pre-defined event locations (black stars). The grid search parameters used for each test are as follows: (a)  $\Delta\phi = 6^\circ$ ,  $v_g = 0.28 - 0.34\text{km/s}$ , (b)  $\Delta\phi = 3^\circ$ ,  $v_g = 0.32 - 0.34\text{km/s}$ , and (c)  $\Delta\phi = 1^\circ$ ,  $v_g = 0.299 - 0.301\text{km/s}$ . Stars show input event locations (red denotes the location of ground-truth UTTR explosions) and gray regions highlight resultant event location uncertainties.**

#### Application to Utah

We have processed Utah seismo-acoustic network data for a period of ~1 month (07/24/07 – 08/28/07) using the previously described detection scheme with the following parameters: Processing window length = 10 s, Overlap = 50%, Frequency Band = 1–5 Hz, Adaptive Window Length (w) = 24 hours, Detection Threshold (p-value) = 0.01. These parameters are specifically tailored for the detection of relatively short, high-frequency arrivals. Such types of signals arise from a range of sources including explosions, mining events, rocket launches, earthquakes, bolides, and impulsive volcanic eruptions at local and regional distances. Our choice of parameters will filter out some

infrasound signals including large events with purely thermospheric arrivals (i.e., those with little high frequencies energy).

After applying the detector to the data, we obtain sets of arrivals at each array (EPU, BGU, and NOQ) in the Utah network (Figure 2). The following parameters are obtained for each arrival: start time, end time, backazimuth, phase velocity, F-statistic, c-value, and correlation. Clear spatial trends are observed in the arrivals at each array, as shown in Figure 2. For example, relatively large numbers of arrivals with Correlation~0.5 are observed from the east at each array.



**Figure 2. Automatic detections obtained at the Utah seismo-acoustic network arrays. In each panel, detections are plotted with respect to time and backazimuth and color-coded by correlation. Some artifacts are observed, associated with lines of detections at constant azimuth, which arise from F-K processing of coherent signals with subsonic group velocities (i.e., winds). The histograms show numbers of detections from each 1-degree bin of backazimuth.**

The three sets of detections are then processed using the association algorithm previously described. We search for signals with group velocities that range from 0.28 to 0.34 km/s, thus ignoring any higher velocity thermospheric

arrivals that may not have been completely removed by the band-pass filter. The following parameters are used: Backazimuth deviation ( $\Delta\phi$ ) =  $6^\circ$  and picking error ( $E_p$ ) = 40 s. Large deviations in backazimuth are allowed in order to compensate for measurement uncertainty (e.g., Szuberla and Olson, 2004) and winds (e.g., Mutschlecner and Whitaker, 2005). The allowed start-time picking error is large due to the emergent nature of many infrasonic signals as well as possible temporal variations in the atmosphere. The result of this analysis is a set of triplets of associated arrivals at all three arrays (or “events”). In total, we obtain 287 events recorded at all three arrays during the period of study. Each event is associated with a set of N grid nodes, which delineates the possible source region for that event.

The final set of event locations is computed by taking the geographic means of the grid nodes associated with each event. The location uncertainties are taken to be the standard deviations of grid node locations in latitude and longitude respectively. The locations of all events recorded at all three of the arrays are shown in Figure 3. Four known rocket motor explosions, conducted at UTTR were automatically detected and located with a mean offset of 5.4 km (and standard deviation of 3.3 km), providing confidence in the automatic catalog. We also detect a number of unknown events, including relatively large numbers of events to the east of the network (possibly due to more sources in this direction or to dominant seasonal winds – which enhance detection of signals to the east of the network during the summer). However, due to the network geometry, which was intended primarily for studying local events, there is a large uncertainty in the range of these events (Figure 4).

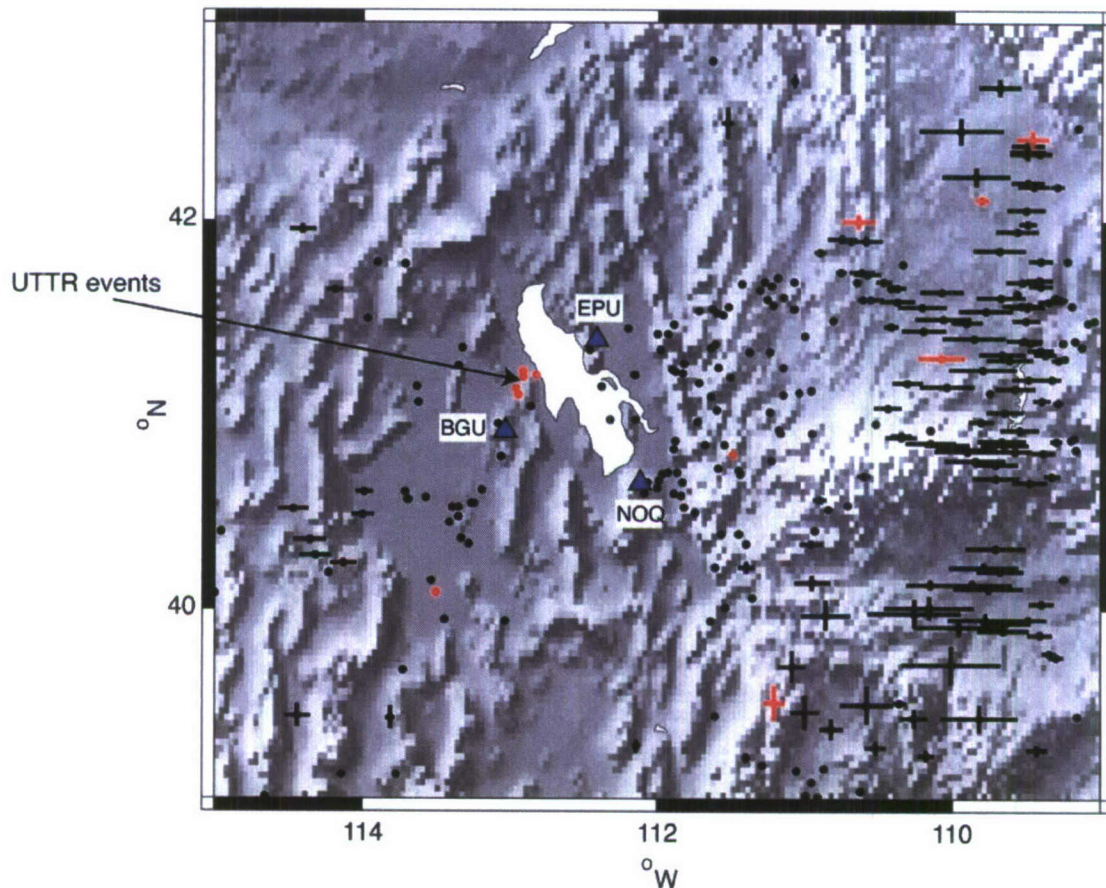
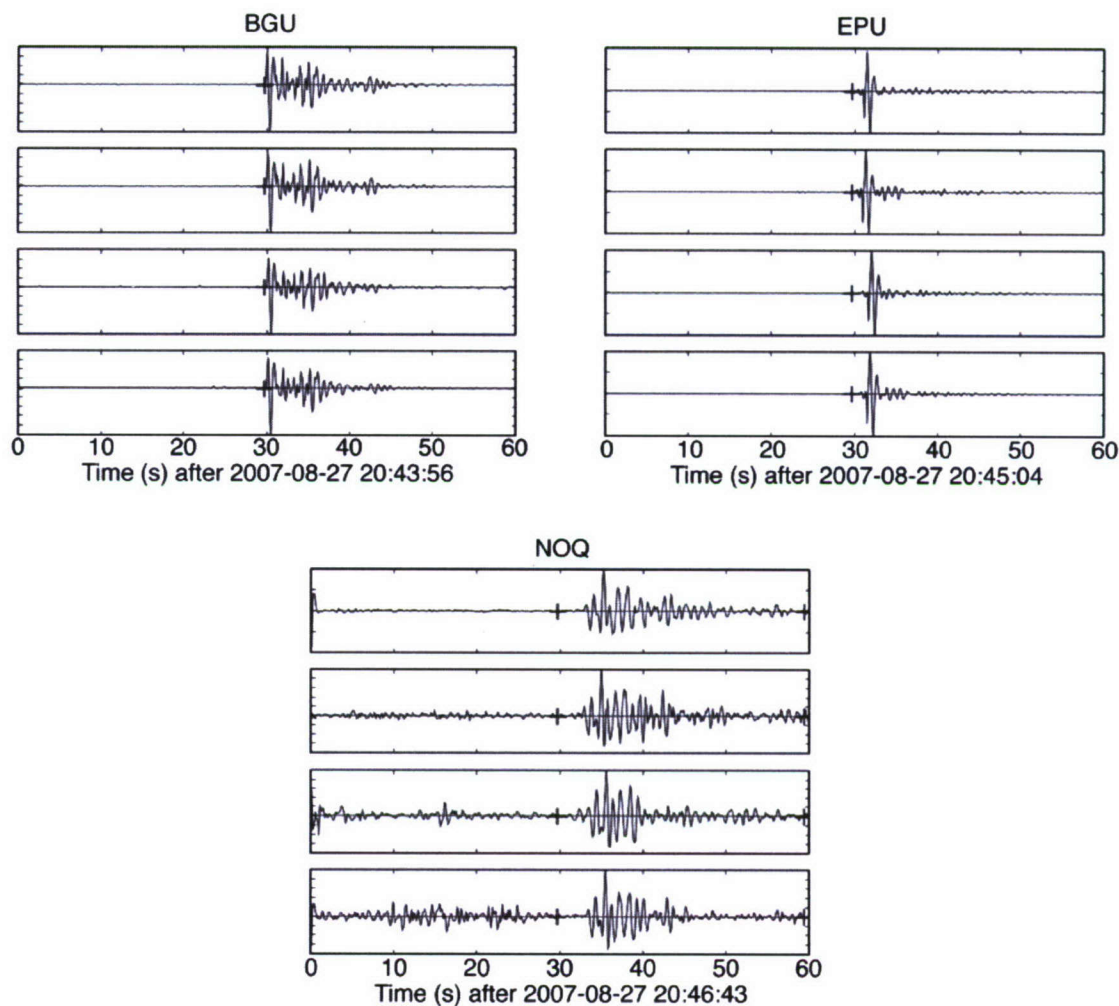


Figure 3. Locations of infrasound (black) and seismo-acoustic (red) events with corresponding uncertainties in latitude and longitude. Blue triangles denote the locations of the three seismo-acoustic arrays.

### Validation by Analyst Review, Ground-Truth, and Google Earth

An analyst has reviewed all infrasound and seismo-acoustic events plotted in Figure 3. Of the 287 events, 70 were marked as excellent, with high signal/noise ratios observed on at least two arrays; 143 were marked as good, with clear signals observed at  $\geq 2$  arrays, but relatively low signal/noise ratios; and 74 were marked as poor, with no obvious signals in the time series.

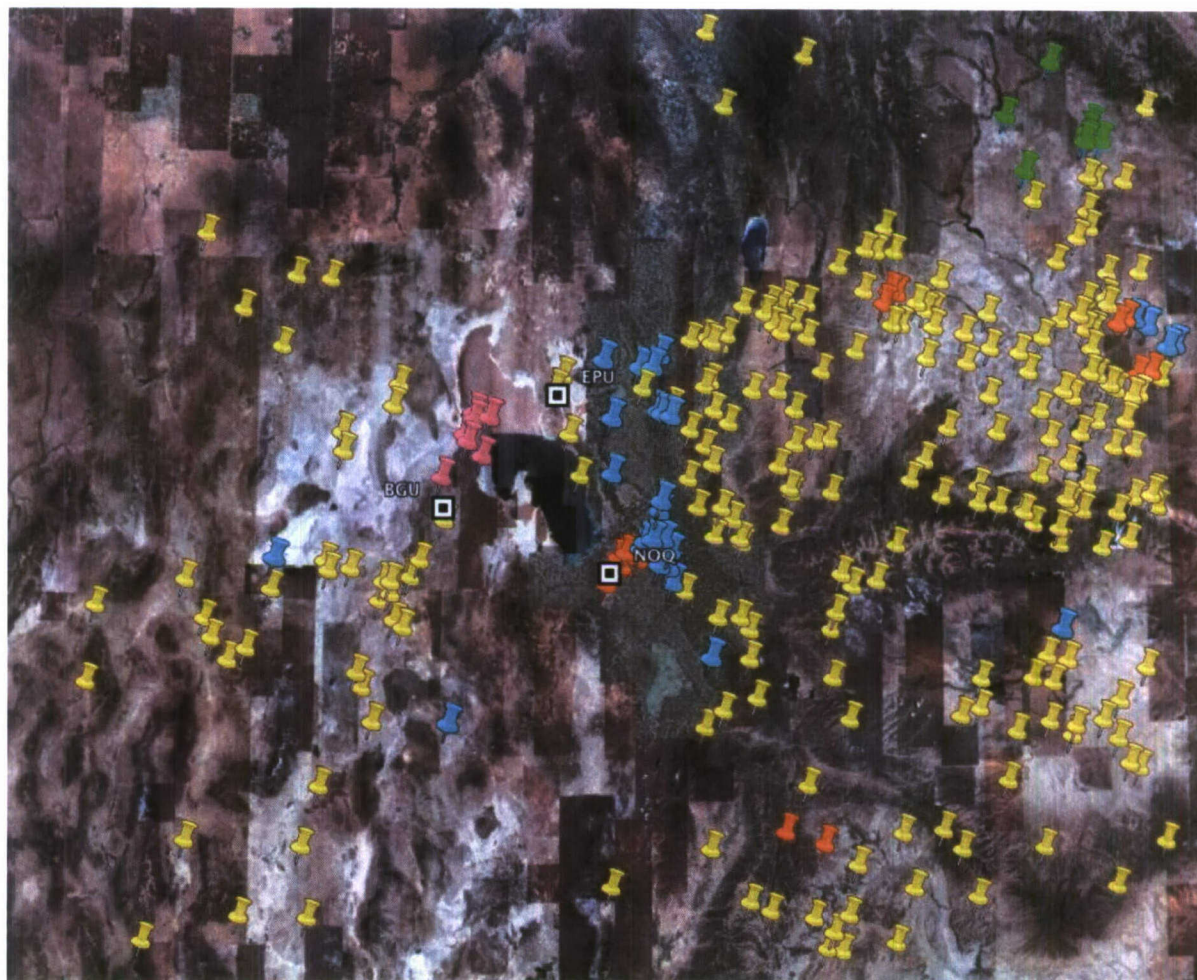
As noted earlier, four rocket motors were detonated at the UTTR during the  $\sim 1$  month survey period. Each of these large events was detected and located by both infrasound and seismic instruments (Figure 3). Infrasound signals at all three arrays, from one of the explosions, are shown in Figure 4. Each explosion is associated with high-quality arrivals at each array, which are automatically associated and located within a mean distance of 5.4 km from the test site. Manually picking onset times, rather than using onset times of detections from the F-detector, should further reduce location errors.



**Figure 4. Automatic waveform detection onset times for a UTTR explosion detected on August 27<sup>th</sup>, 2007. Automatic detection onsets associated with the event are located at 30 s on each panel. The waveform amplitudes are normalized to the maximum amplitude for each trace.**

For the purpose of obtaining additional ground-truth, we have uploaded the event locations into Google Earth, in order to search for tentative location associations (Figure 5). Events within a small radius of potential sources

identified in Google Earth are tentatively associated with that source, and flagged for further analysis (Figure 6). In addition to events occurring at or near the UTTR, we identified four surface-mine locations, numerous airports, and several events that are tentatively associated with an extensive oil and gas drilling field in Wyoming (Figure 5). At the time of writing, the majority of events remain unassociated, although ground-truth association work is at a preliminary stage. However, we note that a significant proportion of events occur in clusters, and that a large number of events are located on mountain peaks, suggesting that they may be associated with storms (common during July and August). Further research is required to investigate these events in more detail.



**Figure 5.** Infrasound locations superimposed on satellite imagery from Google Earth. The colored pointers denote events that are unassociated (yellow), events tentatively associated with the UTTR (purple), events tentatively associated with mines (orange), events tentatively associated with airports (cyan), and events tentatively associated with drilling operations in the Upper Green Valley, Wyoming (green).

## CONCLUSIONS AND RECOMMENDATIONS

This paper briefly outlines new methods for the detection, association, and location of infrasound and seismo-acoustic events. We focus on the application and assessment of these techniques using a test dataset: ~1 month of data from the three-array Utah seismo-acoustic network. During the period of survey, the detection, association, and location algorithms automatically find 287 infrasound events and 12 seismo-acoustic events. Of the 12 seismo-acoustic events, four are associated with known rocket motor explosions at the UTTR, and automatically located within an average distance of ~5 km from the ground-truth location. It must be emphasized that these results

are fully automatic; refinements by manual picking and correction for atmospheric winds are expected to improve results further. The algorithms outlined here are primarily designed to reduce the number of events that require analyst review to practical numbers. A preliminary analyst review and ground-truth survey using Google Earth has found that 70 of the 287 events are associated with high signal/noise signals. Of the remaining events, 74 may be mis-associations (i.e., ~25% of the total number of events), although some of these events are likely to be bona fide events with very low signal/noise ratios. We have tentatively associated events with surface mines, airports, and an extensive oil and gas field. Further work is required to more confidently associate events with these sources and to identify the origins of remaining sources.

In summary, the initial results presented here provide an encouraging preliminary validation of the detection, association, and location algorithms as follows:

- The Utah seismo-acoustic network produced an average of eight events per day.
- The automatic algorithm correctly associated and located all four known ground-truth rocket motor explosion events.
- A comprehensive analyst review has confirmed that < 25% of the events are missassociations.
- A significant number of events have been tentatively associated with sources using Google Earth.
- The remaining un-associated events tend to form clusters, suggesting common origins.



**Figure 6. Zoom on Bingham mine (outlined by white line), showing infrasound events (orange pointers) that are tentatively associated with the mine.**

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